

# Neutron $\beta$ -decay and the quark-mixing CKM-matrix

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## Abstract

Neutrons study a number of hot topics from the field of particle physics and cosmology: Recent measurements of various mixed American-British-French-German-Hungarian-Japan-Russian groups of researchers determine the strength of the weak interaction of the neutron, which gives us unique information on quark-mixing and the question of unitarity. Much to our surprise, with neutron-decay we find a deviation  $\Delta = 0.0083(28)$  from the unitarity condition, an effect that cannot be explained by the current Standard Model of particle physics.

*Key words:* CKM-matrix, Standard Model, unitarity,  $\beta$ -asymmetry, neutron decay

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## 1 Up, charm, top and quark mixing

According to the accepted theory of particles and fields, matter is built from two types of fundamental particles, called quarks and leptons. The strong interaction glues quarks together to hadrons. These quarks are considered to be quantum mechanical mass eigenstates. When such a hadron decays due to the electroweak interaction, the quarks being involved in the process of weak interaction do mix and the mixing is expressed in the so-called CKM-matrix. By convention, the u, c and t quarks are unmixed and all mixing is expressed via the CKM-matrix operating on d, s and b quarks. The Standard Model of elementary particle physics requests that the mixing ends up in a zero-sum, in other words, the CKM-quark-mixing matrix has to be unitary. Unitarity requires that the sum of the squares of the matrix elements for each row and column be unity.

We have studied the mixing of the down quark in the decay of free neutrons. Much to our surprise, with new neutron-decay data the zero-sum of quark-mixing ends up with a significant deviation  $\Delta = 0.0083(28)$ , which is three

times the stated error, an effect that cannot be explained by the current Standard Model of particle physics [1].

## 2 Neutron $\beta$ -decay

In the Standard Model, two free parameters describe neutron  $\beta$ -decay. One parameter is the already mentioned first entry  $|V_{ud}|$  of the CKM-matrix. The other one is  $\lambda$ , the ratio of the vector coupling constant and the axial vector constant. In neutron decay, several observables are accessible to experiment, which depend on these parameters, so the problem is overdetermined and, together with other data from particle and nuclear physics, many tests of the Standard Model become possible. The chosen observables for determining  $|V_{ud}|$  are the neutron lifetime  $\tau$  and a measurement of the  $\beta$ -asymmetry parameter  $A_0$ . The lifetime is given by

$$\tau^{-1} = C|V_{ud}|^2(1 + 3\lambda^2)f^R(1 + \Delta_R), \quad (1)$$

where  $C = G_F^2 m_e^5 / (2\pi^3) = 1.1613 \cdot 10^{-4} s^{-1}$  in  $\hbar = c = 1$  units,  $f^R = 1.71482(15)$  is the phase space factor [2] (including the model independent radiative correction) adjusted for the current value of the neutron-proton transition energy.  $\Delta_R = 0.0240(8)$  is the model dependent radiative correction to the neutron decay rate. The  $\beta$ -asymmetry  $A_0$  is linked to the probability that an electron is emitted with angle  $\vartheta$  with respect to the neutron spin polarization  $P = \langle \sigma_z \rangle$ : [3]

$$W(\vartheta) = 1 + \frac{v}{c} P A \cos(\vartheta), \quad (2)$$

where  $v/c$  is the electron velocity expressed in fractions of the speed of light.  $A$  is the  $\beta$ -asymmetry coefficient which depends on  $\lambda$ . On account of order 1% corrections for weak magnetism,  $g_V - g_A$  interference, and nucleon recoil,  $A$  has the form  $A = A_0(1 + A_{\mu m}(A_1 W_0 + A_2 W + A_3/W))$  with electron total energy  $W = E_e/m_e c^2 + 1$  (endpoint  $W_0$ ).  $A_0$  is a function of  $\lambda$

$$A_0 = -2 \frac{\lambda(\lambda + 1)}{1 + 3\lambda^2}, \quad (3)$$

where we have assumed that  $\lambda$  is real. The coefficients  $A_{\mu m}$ ,  $A_1$ ,  $A_2$ ,  $A_3$  are from [2] taking a different  $\lambda$  convention into consideration. In addition, a further small radiative correction [4] of order 0.1% must be applied.

### 3 The experiment PERKEO and the result for $|V_{ud}|$

The strategy of PERKEO II followed the instrument PERKEO [5] in minimizing background and maximizing signal with a  $4\pi$  solid angle acceptance over a large region of the beam. Major achievements of the instrument PERKEO II are:

- The signal to background ratio in the range of interest is 200.
- The overall correction of the raw data is 2.04%.
- The detector design allows an energy calibration with linearity better than 1%.
- New polarizers and developments in polarization analysis led to smaller uncertainties related to neutron beam polarization.

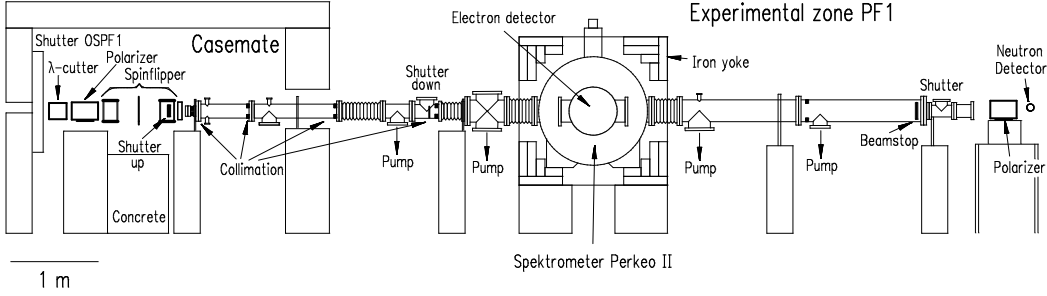


Fig. 1. A schematic view of the whole setup at the ILL.

For a measurement of  $\beta$ -asymmetry  $A_0$ , the instrument PERKEO was installed at the PF1 cold neutron beam position at the High Flux Reactor at the Institut Laue-Langevin, Grenoble. Cold neutrons are obtained from a 25 K deuterium cold moderator near the core of the 57 MW uranium reactor. The neutrons are guided via a 60 m long neutron guide of cross section  $6 \times 12 \text{ cm}^2$  to the experiment and are polarized by a  $3 \times 4.5 \text{ cm}^2$  supermirror polarizer. The de Broglie wavelength spectrum of the cold neutron beam ranges from about 0.2 nm to 1.3 nm. The degree of neutron polarization was measured to be  $P = 98.9(3)\%$  over the full cross section of the beam. The polarization efficiency remained constant during the whole experiment. The neutron polarization is reversed periodically with a current sheet spin flipper. The main component of the PERKEO II spectrometer is a superconducting 1.1 T magnet in a split pair configuration, with a coil diameter of about one meter. Neutrons pass through the spectrometer, whereas decay electrons are guided by the magnetic field to either one of two scintillation detectors with photomultiplier readout. The detector solid angle of acceptance is truly  $2 \times 2\pi$  above a threshold of 60 keV. Electron backscattering effects, serious sources of systematic error in  $\beta$ -spectroscopy, are effectively suppressed. Technical details about the instrument can be found in [6]. The measured electron spectra  $N_i^\uparrow(E_e)$  and  $N_i^\downarrow(E_e)$  in the two detectors ( $i=1,2$ ) for neutron spin up and down,

respectively, define the experimental asymmetry as a function of electron kinetic energy  $E_e$  and are shown in Fig. 2.

$$A_{iexp}(E_e) = \frac{N_i^\uparrow(E_e) - N_i^\downarrow(E_e)}{N_i^\uparrow(E_e) + N_i^\downarrow(E_e)}. \quad (4)$$

By using (4) and with  $\langle \cos(\vartheta) \rangle = 1/2$ ,  $A_{iexp}(E)$  is directly related to the asymmetry parameter

$$A_{exp}(E_e) = A_{1exp}(E_e) - A_{2exp}(E_e) = \frac{v}{c} APf. \quad (5)$$

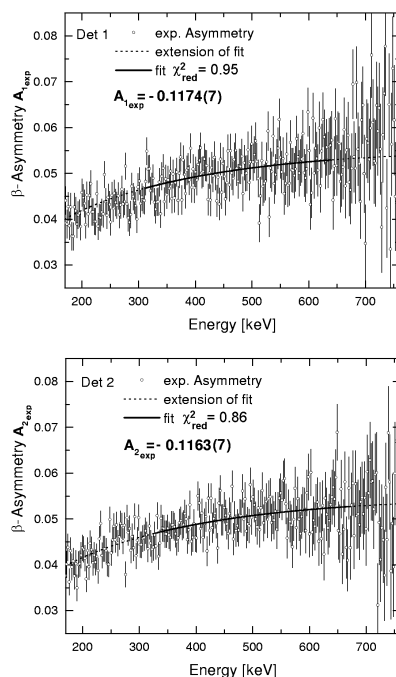


Fig. 2. Fit to the experimental asymmetry  $A_{exp}$  for detector 1 and detector 2. The solid line shows the fit interval, whereas the dotted line shows an extrapolation to higher and lower energies.

The experimental function  $A_{iexp}(E_e)$  and a fit with one free parameter  $A_{iexp}$  (the absolute scale of  $A_0$ ) is shown in Fig. 2. The total correction for the small experimental systematic effects is 2.04%.

With recent experiments from the University of Heidelberg [1,6], we obtain  $A_0 = -0.1189(7)$  and  $\lambda = -1.2739(19)$ . With this value, and the world average for  $\tau = 885.7(7)$  s, we find that  $|V_{ud}| = 0.9713(13)$ . With  $|V_{us}| = 0.2196(23)$  and the negligibly small  $|V_{ub}| = 0.0036(9)$ , one gets

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 - \Delta = 0.9917(28). \quad (6)$$

This value differs from the Standard Model prediction by  $\Delta = 0.0083(28)$ , or three times the stated error. Earlier experiments [7,8,5] gave significant lower values for  $\lambda$ . Averaging over our new result and previous results, the Particle Data Group [9] arrives at a new world average for  $|V_{ud}|$  from neutron  $\beta$ -decay which leads to a 2.2 s deviation from unitarity. Usually,  $|V_{ud}|$  is derived from superallowed nuclear  $\beta$ -decay experiments and this value of  $|V_{ud}|$  includes nuclear structure effect corrections. Combined with kaon, hyperon- and B-decays, this leads to  $\Delta = 0.0032(14)$ , signaling a deviation from the unitarity condition by 2.3 standard deviations [10]. An independent test of CKM unitarity comes from W physics at LEP [11] where W decay hadronic branching ratios can be used expressed in terms of

$$\frac{Br(W \rightarrow q\bar{q})}{1 - Br(W \rightarrow \bar{q})} = (1 + \frac{\alpha}{\pi} \sum |V_{ij}|^2). \quad (7)$$

Since decay into the top quark channel is forbidden by energy conservation one would expect  $\sum |V_{ij}|^2$  to be 2 with a three generation unitary CKM matrix. The experimental result is 2.032(32), consistent with (6) but with considerably lower accuracy.

#### 4 Correlation $B$ and a search for right handed currents

Parity is maximally violated in low energy physics. However, we do not have a fundamental justification for parity violation. It is particularly interesting that modern grand-unified theories support a left-right symmetrical universe right after the start of the big bang. Parity violation arises only due to a spontaneous symmetry breaking at some intermediate energy scale. Parity violation is not 100% and right handed contributions in the weak interaction should be found. Measurements of the correlation coefficient  $B$ , the correlation between neutrino momentum and neutron spin, are sensitive to right handed current contributions in the weak interaction. However, we have no evidence for right handed currents so far. The spectrometer PERKEO II has been installed at the new beam position PF1B for a measurement of coefficient  $B$ . The basic principle of a coefficient  $B$  measurement is to measure the charged decay particles in neutron decay in order to reconstruct the neutrino momentum with respect to the neutron spin. Usually this is done with one electron and one proton detector. PERKEO has one electron detector and one proton detector in each hemisphere. This is an advantage over other experiments because it maximizes the sensitivity on  $B$ . What is more,  $B$  shows in a reasonable region no energy dependence on the decay electrons. Systematic errors due to the detector response function are small. The proton is measured in coincidence with a decay electron. The  $\beta$ -detectors are made of plastic scintillators. The proton

detectors also make use of the  $\beta$ -detectors. The idea is to convert a proton into an electron signal. A proton will be accelerated up to 30 keV and eventually hit a thin foil of carbon. About five secondary electrons will be created and detected with the electron detectors. This method of proton detection was already used by Stratowa et al. [12]. for a measurement of coefficient  $a$ . Measurements are underway and first results are expected soon.

## 5 Summary

In summary,  $|V_{ud}|$ , the first element of the CKM matrix, has been derived from neutron decay experiments in such a way that an unitarity test of the CKM matrix can be performed based solely on particle physics data. With this value, we find a  $3\sigma$  standard deviation from unitarity, which conflicts the prediction of the Standard Model of particle physics. This work was funded by the German Federal Ministry for Research and Education under contract number 06HD953.

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